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Article

Impacts of Urbanization on River Systems in the Taihu Region, China

Xiaojun Deng [1,2], Youpeng Xu [1,*], Longfei Han [1], Song Song [1], Liu Yang [1], Guang Li [1] and Yuefeng Wang [1]

[1] School of Geographic and Oceanographic Science, Nanjing University, Nanjing 210023, China; E-Mails: mijun45@163.com (X.D.); hanlf.nju@gmail.com (L.H.); happysong_song@163.com (S.S.); palapalayl2006@126.com (L.Y.); liguangda1988@163.com (G.L.); wyf2046@163.com (Y.W.)

[2] School of Environmental and Resource Science, Guangxi Normal University, Guilin 541004, China

* Author to whom correspondence should be addressed; E-Mail: xuyp305@163.com; Tel.: +86-25-8359-5069.

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Abstract: River systems are valuable to human beings; meanwhile, they are intensively influenced by human activities, especially urbanization. In this study, based on the data derived from topographic maps and remote sensing images, the temporal and spatial change of river system geomorphology in the Taihu Region over the past 50 years was investigated in conjunction with urbanization. Results demonstrated that the number of river systems decreased drastically, that the morphology of river channels changed into wider and straighter and that the structure of river network tended to simplify in the Taihu Region in recent 50 years. Meanwhile, the changes in river density, the water surface ratio, the river development coefficient, the main river area length ratio and the box dimension in the rapid urbanization period were much greater than those in the slow urbanization period, but the decrease of river sinuosity in the slow urbanization period was more intense. Moreover, the spatial differences of the changes in the river development coefficient were the largest, and the changes in the river indicators in the low-urbanized regions were the most intense. In addition, the changes in the water surface ratio had the closest correlation with urbanization, and the relational degrees between population urbanization and the changes in river systems were the largest. The results can provide a reliable basis to determine reasonable management and conservation strategies of river systems in the Taihu Region.

Keywords: fluvial geomorphology; river systems; temporal and spatial change; urbanization impacts; Taihu Region

1. Introduction

Over the past several millenniums, river systems have always been extensively altered to meet various human demands, which led to them becoming the most intensively influenced ecosystems by human activities on the Earth [1]. Among these human activities, the influence of urbanization on river systems was the most significant, and 60% of river systems were changed profoundly because of urbanization in the world [2]. The ecological integrity of river systems and river ecosystem function were seriously threatened because of these great changes over the past few decades [3,4]. An increasing number of studies have manifested that the degradation of river structure and function would bring about severe river health issues, such as “urban stream syndrome”, but it was particular disadvantageous for the survival and development of human beings [5–7]. Therefore, investigating the impacts of urbanization on river systems is crucial to the sustainable management and conservation of river basins.

Although humans carried out various activities to change river systems over the last 4000 years, the impacts of human activities on river systems were not introduced and studied as a broad and specific question until the middle of the 20th century [8]. The studies of the impacts of urbanization on river systems have made significant progress over the past 60 years, and these advances have been focusing mainly on rapidly urbanized regions around the world [9]. Overall, the impacts of urbanization on river systems were mainly embodied in the fluvial geomorphology, hydrology and ecology, but the impacts were inconsistent for river systems of different stream orders and human needs [10–12]. Generally, main rivers of a high stream order were widened because of the increase of the runoff volume caused by river channel dredging and impervious surface increases, and tributaries of a low stream order were narrowed gradually or even disappeared because of river channel sedimentation and urban occupation [13–15]. However, there were different impacts in different urbanized regions, and the impacts of urbanization on river systems usually reduced from the city proper to suburbs [16]. Therefore, regional responses of river systems to urbanization are essential to understanding how the river systems are impacted by human activities.

Taihu Basin is one of the regions with the fastest urbanization speed and the highest urbanization level in China. The rapid urbanization caused a series of changes to the river systems and brought about water degradation, flood disasters and other ecological and environmental issues. In recent years, these serious issues have received increasing attention from both local and central governments in China. Moreover, some great events have become headline news around the world, such as the cyanobacteria event in 2007 and the flood event in 1999. In this context, new pollution abatement and flood control work have been planned and implemented in Taihu Basin. Similarly, some basic research concerning the causes of the increasing pollution and flood has been reevaluated and redirected [17–19]. So far, studies on the characteristics of river system changes and the qualitative relationship with urbanization on a small scale have been conducted [16,20,21]. However, previous studies generally focused on describing the changes of river systems in highly urbanized regions, and there were very few studies that paid attention to the quantitative relationship between the changes of river systems and urbanization. Therefore, investigating the impacts of varying degrees of urbanization on river systems on a larger region is indispensable for the sustainable management of Taihu Basin.

In this paper, the major characteristic indicators of river systems and urbanization were identified and derived, and the changes and corresponding relations of these two types of indicators were then used to discuss the impacts of urbanization on river systems in the Taihu Region (the central plain regions of Taihu Basin). The results of our study can provide insight into the characteristic of river system changes under varying degrees of urbanization and provide a reliable basis to determine reasonable management and conservation strategies of river systems in the Taihu Region.

2. Material and Methods

2.1. Study Area

Taihu Basin is located in the center of the Yangtze River delta in eastern China (Figure 1). The topography of Taihu Basin is characterized primarily by a large dish-like depression with a lower center (about 2 m above mean sea level) and a higher relief along the coastal margin (about 4–5 m above mean sea level) [22]. The total basin area is about 36,895 km^2, the western part of which is hilly regions with an area of 7338 km^2; the central part is a lake region with an area of 2338 km^2, and the other 27,219 km^2 are wide plain regions.

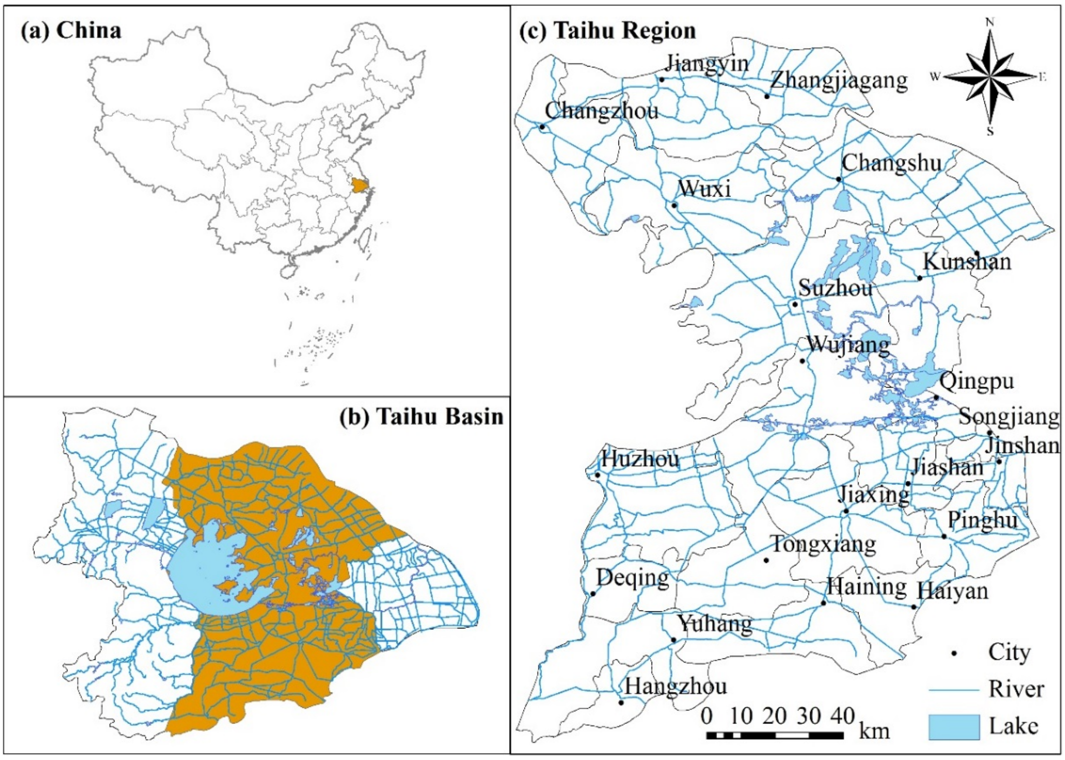

Figure 1. The map of Taihu Region.

Taihu Basin is the most renowned river network region in China. There is water surface area of 5551 km^2, occupying about 15% of the whole basin, a river total length of 120,000 km and a river density of 3.3 km/km^2. Meanwhile, the central basin distributes to many lakes due to the lower topography, such as Taihu Lake, Yangcheng Lake, Dianshan Lake and Cheng Lake. Moreover, river systems of this basin are divided into the upstream and downstream. Some independent river systems in the western hilly regions, including Tiaoxi stream (contributing 50% to runoff sources), Nanhe stream (contributing 25% to runoff sources) and Taoge River streams (contributing 20% to runoff sources), are the upstream. The wide plain river systems are the downstream, including Huangpu River in the eastern part, some rivers flowing into the Yangtze River in the northern part and other rivers flowing into Hangzhou Bay in the southern part.

Unlike other large freshwater lakes in China, a more complex natural and anthropogenic environment exists in Taihu Basin. Due to its lower elevation, Taihu Lake is closely associated with the East China Sea via a dense river network, which leads to it being invariably impacted by typhoon rainstorm in the summer season and the rising tide during winter [23]. Meanwhile, a large number of water conservancy projects have been constructed around the urban and rural areas, such as protective embankments in lakeside areas, water gates, pump stations and dams. These constructions not only met the irrigation, discharge, and navigation needs, but also destroyed the connectivity of rivers and lakes and threaten their natural regulation and purification functions. Moreover, with the rapid development of urbanization (as an example, the proportion of urban land increased from 7.08% in 1991 to 27.16% in 2010), increasing non-point pollution and sewage wastewater via river network inflow to Taihu Lake results in poor water quality [24,25], and increasing water use for production and living bring groundwater overdrafts and result in severer land subsidence (about 1–2 cm annually). Thus, serious pollution and flood disasters are the key challenges that Taihu Basin faces in the future [26,27].

Generally, the flooding of Taihu Basin is caused by the rainfall runoff of the western hilly regions and the rainfall of the central and eastern plain regions. The flooding is discharged to the East China Sea via the regulation and storage of Taihu Lake. Obviously, the plain regions are the key regions for controlling flooding. Therefore, the central plain regions (Taihu Region) were selected as the study area in this paper (Shanghai is excluded due to the presence of some studies). The total area of the Taihu Region is about 15,757 km^2, covering 22 large and medium- and small-sized cities, such as Hangzhou, Suzhou, Wuxi, Changzhou, Jiaxing, Huzhou and Jiangyin. The Taihu Region has been a major economic and cultural center of China since ancient times. Nonetheless, the frequent flood disasters cause enormous economic losses and have hindered the sustainable development of society and the economy in recent decades.

2.2. Data

River systems data were derived from 200 military topographic maps with a scale of 1:50,000 in the 1960s (1960–1963) and 1980s (1983–1985) and a digital line graphic with a scale of 1:50,000 in the 2010s (generated by a local bureau of surveying and mapping in 2009, but verified by us in 2014). The basic elements of river systems are composed of polygons and polylines. The lakes, reservoirs, ponds and main rivers are represented as polygons, and other tributaries are represented as polylines. Meanwhile, the center lines of the main rivers are extracted by ArcGIS for calculating river density, the river development coefficient, river sinuosity, the main river area length ratio and the box dimension. Moreover, in order to calculate the water surface ratio, the widths of tributaries are estimated based on their order.

A common method of designating river orders was established by Strahler in 1952 [28], and its basic idea is as follows: the smallest river connecting directly to the headwater is designated the first-order river;

two first-order rivers are joined in the second-order river; the third-order river is joined by two second-order rivers; and so forth. The river systems were divided into four stream orders in the Taihu Region, according to the aforementioned method and the natural features (the length and width of rivers), as well as the social attributes (the main functions and competent authorities of rivers) of the river systems. Among them, the width of the first-order river was less than 10 m, and the width of the second-order river was between 10 and 20 m. Meanwhile, the width of the third-order river was between 20 and 30 m, and the width of the fourth-order river was wider than 40 m. Moreover, the rivers of the first-order and second-order are regarded as the tributaries, and the rivers of the third-order and fourth-order are viewed as the main rivers.

Population, economic and land use data were used to analyze the urbanization process of every administrative region in the Taihu Region. Eight Landsat TM images (spatial resolution of 30 m) in 1984 and 2010 were used to extract the land use data. With the support of ENVI, the Landsat TM images were interpreted and analyzed, and the land use types were divided into urban land, water area, dry land, forest land and paddy field. Moreover, population and economic data were derived from the statistical yearbook of every administrative region in the Taihu Region during that same period.

2.3. River and Urbanization Indicators

In order to analyze quantitatively the changes of river systems and the urbanization process in the Taihu Region, six river indicators and three urbanization indicators were identified and derived based on fluvial geomorphology and urban geography, as follows.

2.3.1. River Density

River density is the total length of river per unit area in a basin, and it is an important characteristic of river development. Moreover, the storage and discharge capacity of a basin are usually influenced by the river density, especially in the Taihu Region [16]. The expression of river density is:

$$D_r = L/A \tag{1}$$

where D_r is the river density (km/km^2); L is the total river length (km); A is the basin area (km^2).

2.3.2. Water Surface Ratio

The water surface ratio is the ratio of the total area of rivers and lakes under the mean water level to the basin area. It is important to maintain an adequate water surface ratio for urban flood control and the ecosystem service function of water purification, climatic regulation and biodiversity conservation [20,29]. Its computational formula is:

$$W_p = A_w/A \tag{2}$$

where W_p is the water surface ratio (also known as water percentage); A_w is the total area of rivers and lakes under the mean water level (km^2).

2.3.3. River Development Coefficient

Generally, the tributaries constitute more than half of the total river length, and these small rivers dominate the riverine landscape and provide essential functions for the main rivers [30–32]. However, in the process of urbanization, the tributaries are usually filled or diverted through pipes to accommodate the construction of building, roads and bridges [14,33]. Therefore, it is necessary to survey the changes of the tributary length under urbanization. The river development coefficient is the ratio of the total tributary length to the total main river length. It is calculated as:

$$K_{\omega} = L_t/L_m \tag{3}$$

where K_{ω} is the river development coefficient; L_t is the total tributary length (km); L_m is the total main river length (km).

2.3.4. River Sinuosity

Natural sinuosity is an important characteristic of river morphology, and it also forms a rich variety of river habitat [34]. Therefore, river sinuosity has been widely used in river health assessment since the 1980s [35–39]. It can be calculated by the following formula:

$$S_r = \sum_{i}^{m} \frac{L_{ai}}{L} \times \frac{L_{ai}}{L_{si}} \tag{4}$$

where S_r is the river sinuosity; L_{ai} is the actual length of the i-th river (km); L_{si} is the straight-line distance from the i-th river starting point to its terminal point (km).

2.3.5. Main River Area Length Ratio

The main river is not only the main waterway of navigation, but also the important channel of discharge. Therefore, the size of the main river is closely related to human demands. The main river area length ratio is the characteristic indicator of the asynchronous development of the main river area and length. Its computational formula is:

$$R_m = A_m/L_m \tag{5}$$

where R_m is the main river area length ratio (km^2/km); A_m is the total area of main rivers (km^2).

2.3.6. Box Dimension

The geometric pattern of the river network of a basin can be described with a fractional dimension [40]. The box dimension is the simplest and most widely-used characterization indicator of the fractal dimension [41], and it can be used to investigate the scaling properties of the complex structure describing the river basin form and process [42]. Meanwhile, the box dimension of river systems can reflect the developmental stage of stream erosion [43], as follows: (1) river systems are in the young stage when the values of the box dimension are less than 1.6; (2) the value of the box dimension of the mature stage is between 1.6 and 1.89; (3) when the value of the box dimension is between 1.89 and 2.0, it is regarded as in the old stage. The calculation method of the box dimension is:

$$D_0 = -\lim_{r \to 0} \frac{lgN_{(r)}}{lgr} \quad (6)$$

where D_0 is the box dimension; $N_{(r)}$ is the number of boxes with some rivers; r is the side length of the box, and r = 1000, 950, 900, 850, 800, ..., 50 m are used in this paper according to the mean length and density of rivers.

2.3.7. Urbanization Indicators

In urban geography, urbanization is a complex process of the transformation from a rural lifestyle to an urban one. Today, urbanization not only is the growth of cities and towns, but also includes its impacts on the rural countryside. Generally, the main characteristics of urbanization are the increase of urban population, the development of a non-agriculture economy and the expansion of urban land [44]. Consequently, in this paper, the population urbanization level (U_p), economic urbanization level (U_e) and spatial urbanization level (U_s) were used to characterize the urbanization (Table 1). The urban population of every city is the total non-agriculture population in the whole administrative region. Urban land includes the residential, administration and public services, commercial and business facilities, industrial, logistics and warehouse, street and transportation and municipal utilities land, according to the reference of the Code for Classification of Urban Land Use and Planning Standards of Development Land (GB 50137-2011), which was published by the Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD) in 2011 [45].

Table 1. Characteristic indicators and the computational methods of urbanization.

Classification	Characteristic Indicators	Computational Methods
Population urbanization	Population urbanization level (U_p)	The ratio of urban population to total population
Economic urbanization	Economic urbanization level (U_e)	The ratio of non-agricultural GDP to total GDP
Spatial urbanization	Spatial urbanization level (U_s)	The ratio of urban land area to total area

2.4. Grey Relational Analysis

Currently, empirical model and statistical model are usually used to quantitatively analyze the mutual relation between two variables, such as correlation analysis and regression analysis. However, large samples, typical probability distributions and other demands limit the application of these methods to some extent. Grey relational analysis (GRA) is usually used to analyze the mutual relation of different variables, according to the similarities of geometric proximity between different discrete sequences [46]. In practice, the geometric proximity is described by the grey relational degree, which can be arranged in sequential order [47]. An advantage is that the sample and distribution of data are unrestricted in the application of GRA. Further information regarding GRA is available in the literature [48]. However, the changes of river systems and urbanization are continuous, but long time series relevant data acquisition is very difficult. In this paper, GRA is used to analyze the impacts of urbanization on river systems, and the basic steps are as follows:

(1) Setting of the sequences.

The reference sequence is set as:

$$y_i(t) = \{y_i(1), y_i(2), ..., y_i(k)\}, i = 1, 2, ..., m; t = 1, 2,..., k \quad (7)$$

where y is the changes in river indicators; i represents the i-th river indicator; t represents the t-th city of the study area.

The comparability sequence is set as:

$$x_j(t) = \{x_j(1), x_j(2), ..., x_j(k)\}, j = 1, 2, ..., n; t = 1, 2, ..., k \quad (8)$$

where x is the urbanization indicators; j represents the j-th urbanization indicator.

(2) Normalization of the variables.

$$y_i(t)^* = \frac{y_i(t)}{\sum_{t=1}^{k} y_i(t)}, t = 1, 2, 3, ..., k \quad (9)$$

$$x_j(t)^* = \frac{x_j(t)}{\sum_{t=1}^{k} x_j(t)}, t = 1, 2, 3, ..., k \quad (10)$$

where $y_i(t)^*$ and $x_j(t)^*$ are the normalized value of the reference and the comparability sequence, respectively.

(3) Determine the relational coefficients.

$$\xi_{ij}(t) = \frac{\Delta_{min} + \rho\Delta_{max}}{\Delta_{ij(t)} + \rho\Delta_{max}} \quad (11)$$

where $\xi_{ij}(t)$ is the grey correlation coefficient of $y_i(t)$ and $x_j(t)$; Δ_{max} and Δ_{min} are the largest and smallest value of the difference in absolute value between $y_i(t)^*$ and $x_j(t)^*$, respectively; ρ is the distinguishing coefficient, which differentiates the degree of proximity of $y_i(t)$ and $x_j(t)$, such that $\xi_{ij}(t) \in [0,1]$. Generally, the difference of $\xi_{ij}(t)$ is greater when ρ is a smaller value, and $\rho = 0.5$ is widely accepted [46].

(4) Calculation of the relational degrees.

$$\gamma_{ij} = \frac{1}{k}\sum_{t=1}^{k} \xi_{ij}(t) \quad (12)$$

where γ_{ij} is the grey relational degree of $y_i(t)$ and $x_j(t)$.

(5) Sorting the relational degrees.

The grey relational degrees can be sorted in descending order. The impact of $x_j(t)$ with the larger grey relational degrees on $y_i(t)$ is larger.

3. Results

3.1. Total Change of River Systems

As shown in Table 2, river systems of the Taihu Region were changed visibly during the 1960s to 2010s. D_r and W_p showed a declining trend due to the decrease of rivers and the shrinking of lakes. The total length of rivers gradually decreased from 60,366.81 to 50,245.15 km, and the total area of lakes also decreased from 869.71 to 610.21 km^2 during the 1960s to 2010s. Even so, now, the Taihu Region is still a quintessential plain river network region, because of the over 3 km/km^2 D_r and nearly 10% W_p.

Similarly, K_ω and S_r also tended to reduce over the past 50 years. An important reason for this change was the incredible decrease of the natural winding tributaries of the low stream order. The total length of tributaries reduced 11,281.91 km during the 1960s to 2010s. However, a visible difference is detected in the changes in R_m and D_0. R_m first increased and then decreased, but it decreased from a general view. The main reason was that the increase of the total length of the main rivers in the second stage was eight-times the first stage, *i.e.*, the total length increased 128.73 km during the 1960s to 1980s, but it increased 1031.53 km during the 1980s to 2010s. However, the increase of the total area of the main rivers in the second stage was only nearly double the first stage. The change of D_0 continued to decline due to the same reason for D_r. The Taihu Region is a plain river network region; thus, its D_0 should be between 1.89 and 2.00, according to the aforementioned study [43]. However, the actual D_0's in three periods were all less than 1.89, which illustrated that the complexity of the river network was reduced and that the natural development of the river systems was intensely interfered by human beings.

Table 2. Changes of river indicators in the Taihu Region during the 1960s to 2010s.

Years	D_r (km/km^2)	W_p (%)	K_ω	S_r	R_m (km^2/km)	D_0
1960s	3.69	12.00	3.48	1.12	43.91	1.70
1980s	3.43	11.12	3.13	1.10	46.41	1.67
2010s	3.07	9.72	2.44	1.09	43.56	1.59

Overall, due to the decrease of the natural winding tributaries and the shrinking of lakes, as well as the increase of the straighter main rivers, the number of river systems decreased drastically, the morphology of river channels changed into wider and straighter and the structure of the river network tended to simplify in the Taihu Region in the recent 50 years.

3.2. Temporal Change of River Systems

Population urbanization level (the non-agriculture population percentage of the total population in the whole region) was invariably used to describe the urbanization process [49]. Based on the demarcation points of 30% and 70%, the urbanization process was usually divided into the initial stage, the acceleration stage and the terminal stage [50,51]. The population urbanization level of the Taihu Region was calculated as 29.22% and 40.18%, respectively, according to the statistical population data of the study area in the 1980s and 2010s. Therefore, in order to better analyze the changes of river systems in different urbanization periods, the total urbanization process of the Taihu Region was divided into two periods, 1960s–1980s and 1980s–2010s. The first one was regarded as the slow urbanization period, while the second one was a rapid urbanization period.

The direction and magnitude of the change in each river indicator in different periods are not exactly the same (Figure 2). Among them, D_r, W_p, K_ω and D_0 all show a decreasing trend, but the magnitudes of the changes in four indicators during the rapid urbanization period are about twice those in the slow urbanization period. This demonstrates that the decrement of D_r, W_p, K_ω and D_0 is quickened in the rapid urbanization period. Unlike the changes in the four indicators above, although the change in S_r has been decreasing in the recent 50 years, the decrement of S_r in the slow urbanization period is higher than the rapid urbanization period. R_m increased in the slow urbanization period. However, it decreased in the rapid urbanization period and shows an overall decreasing trend in the recent 50 years.

In conclusion, the changes in D_r, W_p, K_ω, R_m and D_0 in the rapid urbanization period were much greater than those in the slow urbanization period, but the decrease in S_r in the slow urbanization period was more intense than that in the rapid urbanization period.

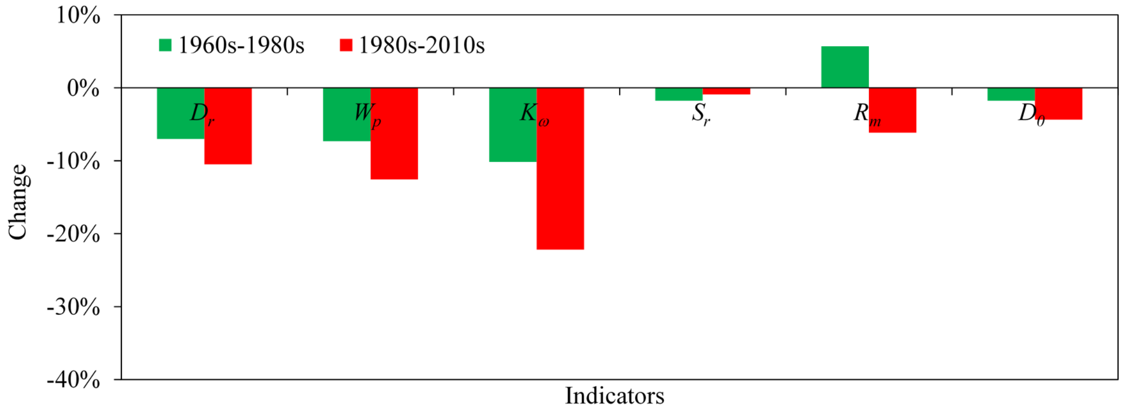

Figure 2. The direction and magnitude of river system changes in the Taihu Region in different periods.

3.3. Spatial Change of River Systems

According to the aforementioned classification method of the urbanization process and the relevant population statistical data of the Taihu Region in the 1980s and 2010s, 22 cities (including the urban center and the urban fringe area in the administrative region of every city) were divided into three categories, respectively. As shown in Figure 3a, Hangzhou is considered the high-urbanized region due to the U_p being greater than 70% in the 1980s. Meanwhile, many medium cities, including Suzhou, Wuxi and Changzhou, are viewed as medium-urbanized regions, because the U_p is between 30% and 70%. Moreover, other small cities are viewed as low-urbanized regions, because the U_p is below 30%, such as Haining and Haiyan. As shown in Figure 3b, Hangzhou is still the high-urbanized region, and Suzhou, Wuxi and Changzhou are also medium-urbanized regions. However, the urbanization levels of 10 small cities increased rapidly, so that they were divided into medium-urbanized regions in the 2010s, such as Huzhou, Songjiang, Zhangjiagang, Changshu and Kunshan.

The changes in river indicators during the 1960s to 1980s have visible differences in different regions (Figure 4). The changes in D_r in the low-urbanized regions are larger than those in the medium-urbanized regions, but they are much larger than those in the high-urbanized region, such as the decrement in D_r being 30.24% and 29.23%, respectively, in Haiyan and Haining, but 5.47% in Hangzhou. Similarly, the changes in K_ω, S_r, R_m and D_0 in the low-urbanized regions are all the largest, but the changes in the high-urbanized regions are much larger than those in the medium-urbanized regions. As an example, the changes in K_ω are about 10.00% in Suzhou, Wuxi and Changzhou, but the decrements in K_ω in Haiyan and Haining are all over 30.00%. However, the changes in W_p in the high-urbanized regions are larger than those in the low-urbanized regions, but they are much larger than the medium-urbanized regions, such as the decrement in W_p being about 5.00% in Suzhou, Wuxi and Changzhou, but Hangzhou increases 17.52%. Compared with other river indicators, the changes in S_r and D_0 are relatively small, and the maximum decrement is only about 10.00%.

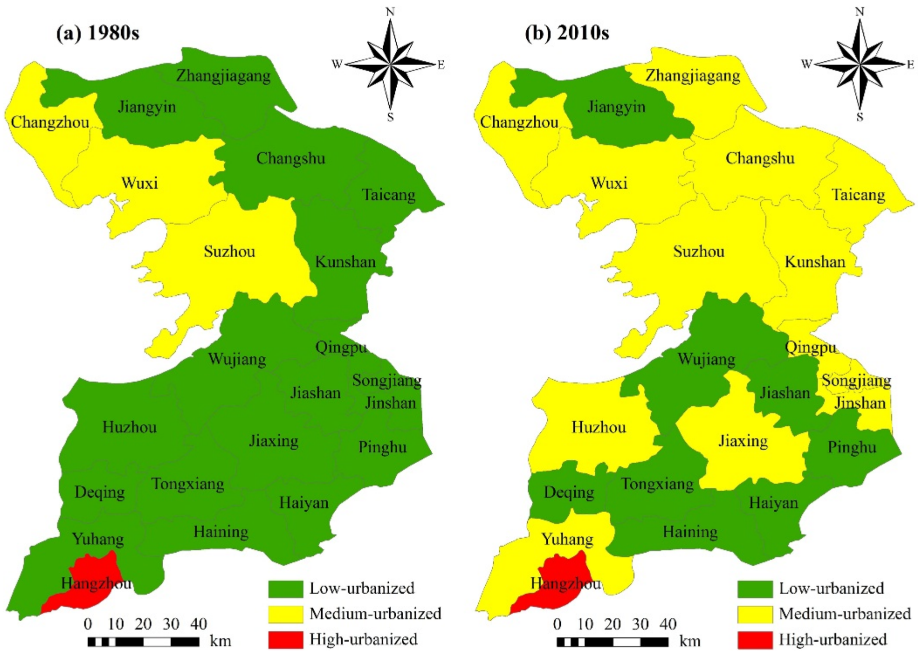

Figure 3. Different urbanization levels of 22 cities of the Taihu Region in the 1980s and 2010s.

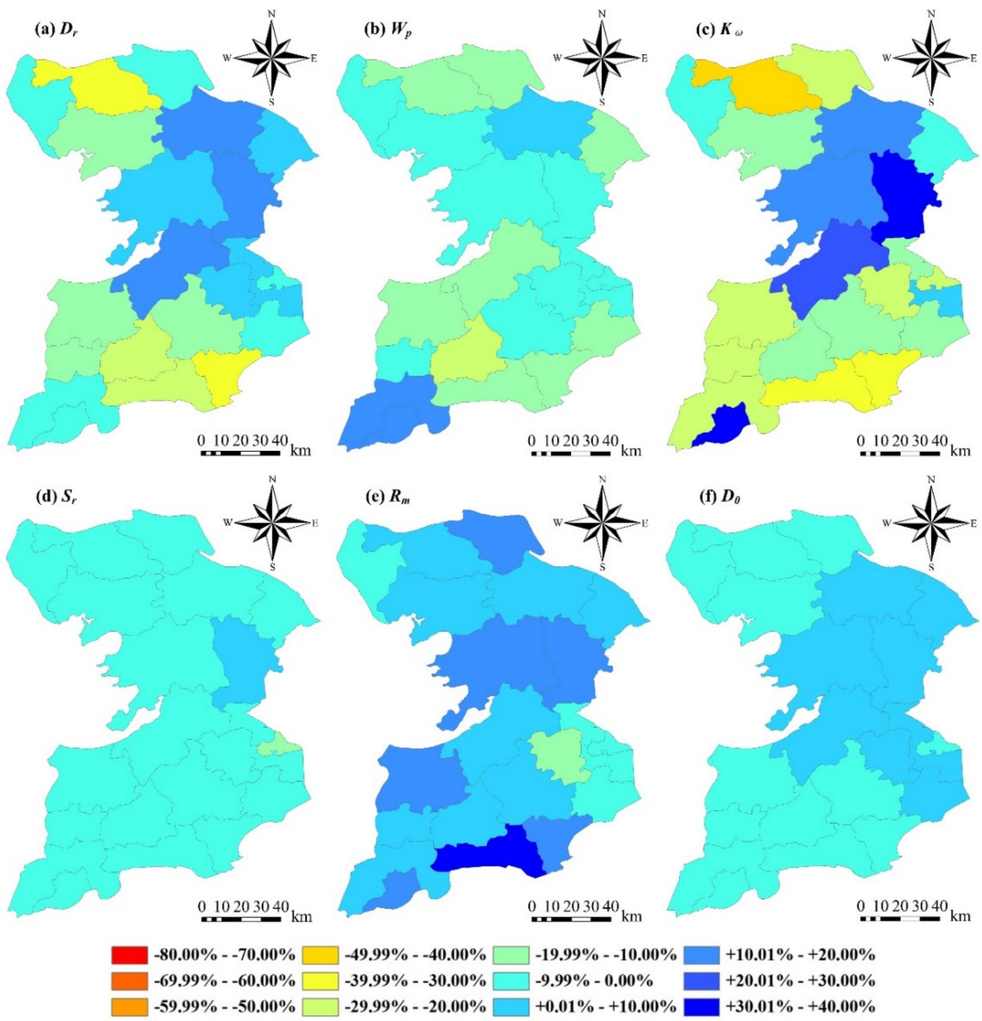

Figure 4. Spatial difference of river system changes in the Taihu Region during the 1960s to 1980s.

As shown in Figure 5, the changes in the river indicators during the 1980s to 2010s also have visible differences in different regions. However, the change in the same indicator in the rapid urbanization period is clearly different from that in the slow urbanization period. The changes in D_r, R_m and D_0 in the high-urbanized region are all the largest, and the changes of the three indicators in the medium-urbanized regions are much larger than the low-urbanized regions. For instance, the decrement in D_r is 20.28% in Hangzhou, but the change in Deqing is almost zero. Meanwhile, the increase in R_m is 15.23% in Hangzhou, but the decrement is only 1.04% in Pinghu. Despite the changes in D_0 being unequal in different regions, the maximum decrement is less than 10.00%. The changes in W_p in the rapid urbanization period are quite different from than those in the slow urbanization period. Those in the medium-urbanized regions are larger than the high-urbanized region, but those in the low-urbanized regions are the smallest, such as the decrement in W_p being 31.23% in Yuhang, but only 2.07% in Haiyan. On the contrary, the changes in K_ω are almost entirely the same in the two periods. As an example, the decrements in K_ω in Haiyan and Tongxiang are both over 60.00%, but 0.55% in Suzhou. Moreover, the difference of the changes in S_r is extremely small, and it is less than 5.00% in general.

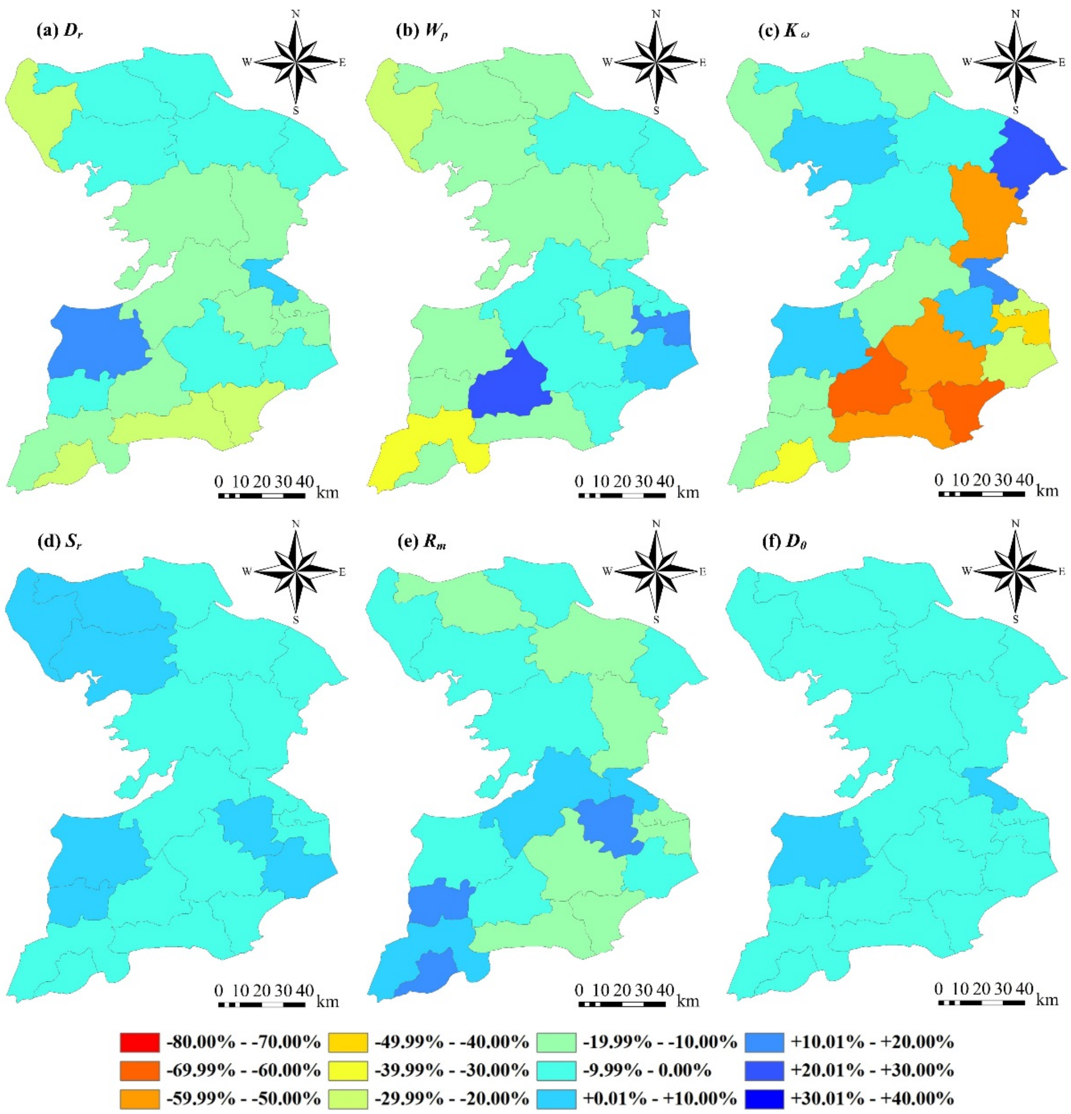

Figure 5. Spatial difference of river systems changes in the Taihu Region during the 1980s to 2010s.

In conclusion, there were wide spatial differences in river system changes in the Taihu Region over the past 50 years. Compared with other river indicators, the spatial differences of the changes in S_r and D_0 are relatively small. However, the spatial differences of the changes in K_ω were the largest. Meanwhile, the changes in river indicators in the low-urbanized regions were the most intense as a whole.

3.4. Impacts of Urbanization on River Systems

The aforementioned analysis demonstrated that the changes in river indicators were distinguishing in temporal and spatial scales. In order to further analyze the impacts of urbanization on river systems in different periods and regions, the changes in six river indicators of river systems in 22 cities of the Taihu Region were set as the reference sequence, and three urbanization indicators were set as the comparability sequence. According to the basic steps of GRA, the grey relational degrees can be calculated and sorted, as displayed in Table 3.

Table 3. The grey relational degrees between the changes in river indicators and urbanization indicators.

1960s–1980s	D_r	W_p	K_ω	S_r	R_m	D_0	**Average**
U_p	0.6138	0.7534	0.6923	0.7290	0.7493	0.6945	0.7054
U_e	0.6076	0.6962	0.6699	0.7521	0.7647	0.6005	0.6818
U_s	0.6085	0.7605	0.7615	0.6609	0.7133	0.5964	0.6835
Average	0.6100	0.7367	0.7079	0.7140	0.7424	0.6305	--
1980s–2010s	D_r	W_p	K_ω	S_r	R_m	D_0	**Average**
U_p	0.6793	0.6900	0.6349	0.6736	0.6753	0.7011	0.6757
U_e	0.6830	0.6994	0.6323	0.6701	0.6358	0.6728	0.6656
U_s	0.6494	0.7052	0.6264	0.7113	0.6108	0.7064	0.6683
Average	0.6706	0.6982	0.6312	0.6850	0.6406	0.6934	--

As shown in Table 3, the changes in river indicators and urbanization indicators are highly correlated with each other. Meanwhile, all of the grey relational degrees are greater than the distinguishing coefficient of GRA ($\rho = 0.5$). This indicates that the urbanization indicators are significantly positively correlated with the changes in river indicators. However, different urbanization indicators have different correlations with the changes in river indicators in different urbanization periods. Only U_s has the maximum correlation with the change in W_p in two urbanization periods, and the order of the grey relational degrees of three urbanization indicators is as before. This indicates that the expansion of the urban land shows the most significant correlation with the decrease of W_p in the Taihu Region.

During the slow urbanization period, the average grey relational degrees of the changes in river indicators can be sorted in descending order as $R_m > W_p > S_r > K_\omega > D_0 > D_r$, and the average grey relational degrees of urbanization indicators can be sorted in descending order as $U_p > U_s > U_e$. Similarly, during the rapid urbanization period, the descending order of the average grey relational degrees of the changes in river indicators is as follows: $W_p > D_0 > S_r > D_r > R_m > K_\omega$; while the average grey relational degrees of urbanization indicators can be sorted in descending order as $U_p > U_s > U_e$. This indicates that the urbanization indicators are significantly correlated with the changes in R_m in the slow urbanization period, and they are significantly correlated with the changes in W_p in the rapid urbanization period;

however, U_p always shows the most significant correlation with the changes of river systems in the two periods.

Overall, the changes in river systems were closely correlated with urbanization; however, the changes in W_p had the closest correlation with urbanization, and the relational degrees between U_p and the changes in the river systems were the largest in the Taihu Region.

4 Discussions

4.1. River Systems Changes

The aforementioned analysis presented that changes in the quantitative, morphological and structural features of river systems were detected in the Taihu Region over the past 50 years, and these changes were distinguished in different periods and regions. These results are almost consistent with the results of similar plain river network regions, such as Shanghai, Ningbo and Shenzhen [16,52,53], which indicates that the results in this study are reliable.

Overall, river systems in the Taihu Region tended to decrease, and these changes were much greater in the rapid urbanization period than the slow urbanization period due to the following reasons. On the one hand, in order to improve the capacities of storage and discharge, the main rivers were usually dredged and reconstructed in the Taihu Region during the slow urbanization period. Meanwhile, the tributaries were also straightened, widened and changed into the main rivers [54]. These artificial changes led to the higher rate of decrease of K_ω and S_r and the increase of R_m. In addition, for the sake of flood control and irrigation in suburbs and country areas, numerous protective dam, water gates, lakeside embankments and comprehensive farmland improvement facilities were constructed. Unfortunately, many of the low-order tributaries were buried, and the connectivity between the main rivers and the tributaries was cut off and gradually disappeared in this process. For the purpose of gaining more farmland, the fringe areas around the lakes were also reclaimed [55]. Thus, D_r, W_p and D_0 were showed a declining trend in the slow urbanization period. On the other hand, since the reform and opening up in 1979, the Taihu Region became one of the main districts of the rapid urbanization process in China, especially in the wide suburbs. In order to develop industry and improve public facilities, a multitude of low-order tributaries and small water bodies were occupied by impervious surfaces [4,15]. These changes led to the more intense decrease of D_r, W_p, K_ω and D_0 in the rapid urbanization period than the slow urbanization period. In addition, the decrease of the tributaries and water bodies and the increase of impervious surfaces also resulted in the increase of flood risk [56]. In order to release flooding, a multitude of low-order tributaries were widened and changed into main rivers. In this context, the total length of the main rivers was rapidly increased, but the increase of the total area was limited due to land requirements, especially in urbanized regions. Therefore, R_m was decreased intensely in the rapid urbanization period. In contrast, the decrease of S_r in the slow urbanization period was more intense, which might be related to a host of winding rivers that had been straightened during the extensive water conservancy constructions [21,39].

In addition, there are several possible reasons for the spatial differences of river systems changes. Firstly, the administrator in different regions changed the river systems for different purposes. As an example, the low-urbanized regions, generally dominated by agriculture, resulted in the needs of irrigation and flood control. Headwater streams were buried to increase the amount of arable land available in these areas [57,58]. However, the high-urbanized region was mainly metropolitan area, and their river systems were changed to meet the needs of urban development. Secondly, the original values of river indicators were different in different regions. As an example, D_r in Haiyan in the 1960s was 5.31 km/km^2, but it was 1.75 km/km^2 in Hangzhou. Therefore, it was feasible that D_r in Haiyan decreased to 1.75 km/km^2 (the real D_r in the 2010s was 2.85 km/km^2), but it was forbidden that D_r in Hangzhou decrease to zero (the real D_r in 2010s is 1.32 km/km^2). Last but not the least, there were wide spatial differences in the distribution of the tributaries. Generally speaking, the total length of tributaries in the high-urbanized region was overwhelmingly limited due to the continuous urban development for several hundreds or thousands of years, but it was larger in the low-urbanized regions due to relatively little interference by human beings. For example, the total length of tributaries in Haiyan in the 1960s was 2324.75 km, but in Hangzhou only 395.12 km.

4.2. Urbanization Impacts

Most of the research has indicated that river systems are changed by various urbanization factors [9,14]. However, few researchers have paid attention to the distinction of the impacts of different urbanization factors on river systems. Based on the results of GRA, we believe that the changes in river systems and urbanization are closely correlated with each other in the Taihu Region, but the relational degrees between different river and urbanization indicators are distinguished in different urbanization periods.

From 1950 to 2014, the population residing in urban areas in the world increased form 30% to 54% [49]. Population growth in urban areas brought about the development of real estate, business, industry and transportation and resulted in the changes of land use ultimately [44]. In this process, a multitude of low-order tributaries and small water bodies were occupied and buried, weakening the storage capacities and discharge of river systems [4,15]. Wide construction of buildings, roads and bridges all over the cities led to the geometric increase of impervious surfaces [9,14,56]. The rapid expansion of impervious surfaces reduced the infiltration rate and roughness condition, but increased the flood risk [7]. One possible solution to lower the flood risk is to improve the catchment storage and drainage capacities by straightening and merging the winding streams, dredging and channelizing the main rivers, *etc.* [2,14,54]. Meanwhile, floodwalls, dams and gates were constructed in urban areas, and protective lakeside embankments were strengthened and extended in suburban areas for better control of flooding. These artificial hydraulic constructions cut off the natural connectivity between rivers and lakes and formed independent small rivers and lakes, which were buried and disappeared ultimately [31,32]. Therefore, it can be seen that population urbanization might be the primary influence factor of river system changes, and W_p might be the most sensitive factor to the effects of urbanization.

5 Conclusions

In this paper, the temporal and spatial change of river systems geomorphology in the Taihu Region over the past 50 years was analyzed in conjunction with urbanization. Through comprehensive analysis, the following conclusions have been gained:

(1) The number of river systems decreased drastically, the morphology of river channels changed into wider and straighter and the structure of the river network tended to simplify in the Taihu Region in the recent 50 years; due to the decrease of the natural winding tributaries and the shrinking of lakes, as well as the increase of the straighter main rivers.
(2) Under the influence of drastic land use change and increasing flood risk, the changes in D_r, W_p, K_ω, R_m and D_0 in the rapid urbanization period were much greater than those in the slow urbanization period. However, the decrease of S_r in the slow urbanization period was more intense, which might be related to a host of winding rivers having been straightened during the extensive water conservancy constructions.
(3) There were wide spatial differences in river system changes in the Taihu Region over the past 50 years. In contrast, the spatial differences of the changes in S_r and D_0 are small, but the spatial differences of the changes in K_ω were the largest. Furthermore, the changes in river indicators in the low-urbanized regions were the most intense.
(4) The changes in river systems were closely correlated with urbanization; however, the changes in W_p had the closest correlation with urbanization, and the relational degrees between U_p and the changes in river systems were the largest in the Taihu Region.

In conclusion, it is discernible that the changes of river systems are influenced primarily by urbanization in the short term. Nevertheless, the respective contributions of population urbanization, economic urbanization and spatial urbanization to river system change in the Taihu Region should be further quantified. Moreover, further studies using more river and urbanization indicators from other regions are required to strengthen the conclusions concerning the impacts of urbanization on river systems. In addition, more studies should be conducted on the impacts of river system changes and urbanization on the change of hydrologic connectivity and water level in the Taihu Region, mainly for providing a better scientific basis and decision-making reference for the planning, management and conservation of river systems in the Taihu Region.

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Author Contribution

Youpeng Xu conceived the manuscript; Xiaojun Deng performed data analysis and wrote the manuscript; Longfei Han and Song Song contributed to revise and proofreading; Liu Yang, Guang Li and Yuefeng Wang collected and processed data.

Conflicts of Interest

The authors declare no conflict of interest.

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